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L-321

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SUMMARY

A study has been made of underslung cooling ducts with special reference to the problems presented by the boundary layer on the fuselage skin. It was found that good flow can be obtained in such ducts by (1) making the inlet opening of such size that the mean inlet velocity is about 0.6 the free-stream velocity and (2) providing vanes behind as well as ahead of the radiator. Tables to facilitate design are included, together with an example.

INTRODUCTION

On a number of modern airplanes the air inlet for the cooling system is located on the fuselage at some distance from the nose. Experience with this type of installation has indicated that, unless certain precautions are taken in its design, the drag will be excessive. Owing to the existence of the boundary layer on the fuselage skin, special problems arise regarding (1) the size of the duct inlet and (2) the arrangement of guide vanes within the duct. These problems have been studied with the aid of some wind-tunnel experiments, and two duct designs have been tested in order to show the validity of the proposed solutions. Tables are included giving the relationship of the various duct dimensions and the spacing of the guide vanes for a range of boundary-layer conditions existing on a fuselage.

SYMBOLS

V velocity

q dynamic pressure

p static pressure, with reference to free-stream static pressure

H	total pressure, $p + q$
ν	kinematic viscosity
x	distance from nose of fuselage
y	distance from fuselage skin
S	area
D	drag
δ	boundary-layer thickness
Δp	pressure drop across radiator
k	$\Delta p/q$ for the radiator
i	height of rectangular duct inlet
e	height of rectangular duct outlet
r	height of rectangular radiator
Q	volume of cooling air flow per second

Subscript:

o	free stream

PRINCIPLES OF DESIGN

The optimum duct inlet.- Unlike the expansion of the air flow in front of an N.A.C.A. cowling, the permissible expansion in front of a fuselage-duct inlet is limited by the fact that the boundary layer will break away from the skin if it is subjected to too large an adverse pressure gradient (fig. 1). The inlet must therefore be of such size that the cooling air required for the design condition expands as much as possible in front of the inlet without break-away; too large an opening not only occasions losses in the flow into the opening but also, unless the nose of the duct is curved sharply inward, causes break-away of the flow over the nose, as indicated in figure 1.

L-321

The optimum vane arrangement.- Inasmuch as only a limited velocity reduction is permissible in front of the duct inlet, the reduction must, for low-velocity cooling, be continued within the duct. Usually this expansion must be quite rapid, for in general only a small space will be available for the entire cooling installation. An expansion angle of about 10° (two-dimensional), such as is frequently used for maximum efficiency, is thus impossible because of the length of duct required. However, by the use of vanes, a large-angle expansion can be divided into several small-angle expansions with a reasonable efficiency.

Here again, however, the boundary layer introduces a complication. Thus consider (fig. 2a) that the air entering the duct is divided into two equal parts and expanded in two adjacent passages. The air entering the upper section has the lower dynamic pressure; accordingly, after the expansion it has the lower static pressure, and this difference still exists behind the radiator. Such a situation is clearly impossible, as the two adjacent streams of air behind the radiator must have the same static pressure. Actually, in such a case, the air flow adjusts itself to that shown in figure 2b. The flow into the lower section increases while that into the upper section decreases. The expansion and radiator losses, which are roughly proportional to the square of the velocity, increase in the lower section and decrease in the upper section, so that the two air streams now leave the radiator at the same static pressure. If the radiator has a relatively high resistance, only a slight readjustment of the flow quantities occurs; if the radiator has a relatively low resistance, the readjustment may leave practically no flow in the upper section, in which case half the radiator would be useless and the advantages of low-velocity cooling would be destroyed. The usual radiator has a resistance sufficiently low for this latter condition to be approached.

The flow may be made to divide equally, however, by means of a short vane behind the radiator, forming a continuation of the forward vane, adjusted to restrict the outlet of the lower section (fig. 2c). The velocity at the lower outlet is thus increased, so that the static pressure is reduced to that at the outlet of the upper section.

EXPERIMENTAL

Wind-tunnel tests were made in order to obtain quantitative information regarding the permissible expansion of a turbulent boundary layer in front of a duct inlet and also to verify the efficacy of the proposed arrangement of rear vanes.

The work was done in the 1/15-scale model of the NACA full-scale wind tunnel, converted for these tests to a closed rectangular tunnel 2 by 2.75 feet (fig. 3). The duct was mounted in the floor of the test section, which thus represented the fuselage skin. The air speed was about 60 miles per hour for all the tests. Turbulent boundary layers of various thicknesses were produced on the floor of the test section by placing various obstructions across the floor of the entrance cone. Double celluloid windows were provided in both sides of the duct in order to permit tuft observations. The rear half of the top of the duct was hinged, for adjustment of the rear opening. Two different resistances were used to simulate the radiator, a 40-mesh copper screen for which $\Delta p/q$ was 4.0 and three layers of 100-mesh brass screen for which $\Delta p/q$ was 40. The $\Delta p/q$ of the latter resistance greatly exceeds that for a Prestone or oil radiator; however, it is approached by some intercoolers. The inlet opening was 3.25 inches for the tests with the low-resistance screen, and 2.75 inches for the tests with the high-resistance screen and for the boundary-layer expansion tests. Both screens and vanes were removed for the boundary-layer expansion tests.

Flow measurements were made by means of small total-pressure and static tubes. Determinations of the total drag of the duct installations were made by means of a rake of 40 total-head tubes, 1/8 inch apart, mounted on the floor of the tunnel about 5 inches behind the duct outlet.

EXPANSION AT THE INLET

The expansion of the air in front of the duct inlet was effected by restricting the duct exit. The behavior of the boundary layer was observed by means of a tuft on the floor of the inlet and also by means of survey tubes in the inlet.

The condition of optimum expansion was found difficult to identify. As the exit was restricted through the separation range, the tuft flickered more and more to the front, finally pointing steadily forward in a completely reversed flow; there was no sharp separation point. Also, the air-flow measurements appeared to become more and more inaccurate and inconsistent with increasing expansion, so that it was impossible to determine the energy losses. The readings became particularly erratic, with indications of excessive losses, when the average amplitude of the tuft flicker was much over 30°; so the condition of optimum expansion was somewhat arbitrarily identified as that for which the average amplitude through which the tuft flickered was about 30°. This arbitrary criterion is believed to be satisfactory inasmuch as the range of acceptable conditions appeared to be fairly narrow.

The velocity distributions in four turbulent boundary layers of different thicknesses and the velocity distribution at the inlet when each had been expanded are shown in figure 4. The average inlet velocities for these conditions were about 0.6 the free-stream velocity. The corresponding total- and static-pressure distributions in the inlet are also shown. It will be noted in the figure that δ is defined, not as the largest distance from the skin for which a measurable velocity deficiency exists, but as that value for which the equation

$$\frac{V}{V_o} = \left(\frac{y}{\delta}\right)^{1/7}$$

fits the main part of the velocity profile.

The generality of the results of these boundary-layer tests may be questionable inasmuch as such phenomena vary with Reynolds number. The results discussed in the following section, however, are probably nearly independent of scale.

EXPANSION WITHIN THE DUCT

In the tests that were made to determine the efficacy of the rear guide vanes, a relatively thick boundary layer was used ($\delta/l \cong 0.85$). The front vanes were arranged to permit one-fourth of the total flow to enter smoothly into each of the four passages and to limit the expansion angles of the passages to 10°. The rear vanes were arranged, in accordance with the theory already discussed, so that the flow in all four passages would be the same. The equal distribution of the flow in all four passages was checked by the equal pressure drops across the screen.

Total- and static-pressure measurements were made at the inlet and outlet and behind the duct to determine the internal and external losses of the duct. For comparison, the tests were repeated with the rear vanes removed.

Results.- The Jones drag equation

$$D = 2 \int \sqrt{q} \; (\sqrt{H_0} - \sqrt{H}) \; dS \qquad (1)$$

applied at any section gives the drag of everything upstream of that section. The difference between the drags so calculated for the air leaving the duct and for the air entering the duct is thus the drag chargeable to the inside of the duct. The difference for the air several inches aft of the outlet and several inches ahead of the inlet represents the drag of the entire duct installation. The difference between the drag of the entire installation and the internal drag represents the losses over the outer surface of the duct together with the exit losses at the rear. The exit losses appeared to be negligible since the difference was found to be approximately accounted for, in every case, by the skin friction of the external duct surface.

Table I contains an analysis of the duct drag for the cases of rear vanes in and out. The total drag of the duct with rear vanes in was taken as 100 percent. The efficiencies were computed on the basis of the minimum pump work $Q\Delta p$ across the screen rather than the increment in drag, as found by equation (1), across the screen (reference 1). For the low-resistance screen, the duct efficiency was reduced from 34 percent to 24 percent by removing the rear vanes. For the high-resistance screen, the reduction was from 65 percent to 50 percent. On an actual installation the drag contribution of the external duct surface may be somewhat reduced, with a corresponding increase in efficiency, if the duct is more completely submerged in the fuselage. It should be noted that not the entire friction drag of the duct surface but only the excess over that of the fuselage skin which it replaces is chargeable to the duct.

With the rear vanes in place, the flow was essentially equally divided among the four passages. The distributions of the flow for the cases of rear vanes out are shown in table II. The low flow observed in the second passage, for the low-resistance screen, is probably due to the losses in breaking over the nose of the center vane, as indicated in figure 2b. It may be remarked that, although the nonuniformity of the flow reduces the duct efficiency, it may not greatly reduce the cooling, which depends mainly on the total flow.

DESIGN DIMENSIONS

The design of the passages is determined by the distribution of velocity and total pressure in the expanded boundary layer at the inlet. It is assumed that the flow is divided equally among the passages, and the average total pressure at the inlet of each passage is obtained. It is then assumed that the average total pressure in each passage decreases during the expansion by 12 percent of the average dynamic pressure at the inlet (reference 2). The loss across the radiator, which is the same for each layer, is computed from the known radiator characteristics and the velocity at the radiator. The total pressures and velocities behind the radiator are now known. The constrictions at the ends of the passages are designed according to Bernoulli's equation so that the same static pressure will exist at the ends of two adjacent passages. For calculation of these internal duct dimensions behind the radiator, losses due to mixing at the junctions are neglected. For calculation of the average total pressure (and hence the average velocity) at the exit, these losses are assumed to be half as much as the expansion losses in the forward passages.

Formulas for the design of ducts have been computed for the four inlet conditions shown in figure 4. The results are given in tables IIIa and IIIb for ducts divided into three and four passages, respectively, the expansion angle in each passage being assumed to be 10°. For ducts divided into only two passages, the formulas for the location of the center vanes of the four-passage duct may be used. For the preliminary estimate of δ/i, an approximate value for i may be found by assuming the inlet velocity to be about 0.6 the free-stream velocity; the estimation of δ, however, will generally require some study of the conditions. The results of reference 3 indicate that, for modern single-engine airplanes, δ will be given with satisfactory accuracy by the formula

$$\delta = 0.37 \left(\frac{\nu}{V_o}\right)^{1/5} x^{4/5}$$

It has been assumed here that the radiator and passages are rectangular in cross section, the analysis having been essentially two-dimensional. If they are not rectangular, the design of the rear vanes may be modified by simply substituting relative areas for relative heights. The inlet of the duct should be of uniform height in any case, for it was found that if there was spanwise variation in the total pressure of the air entering an expanding duct, the air having the lowest total pressure broke away a short distance down the duct and spoiled the flow.

Example.- The given procedure has been applied to the following case:

Radiator cross section .	25 inches by 16 inches (r = 16 in.)
$\frac{\Delta p}{q}$	5.0
Cooling air required . .	20,000 cubic feet per minute
Air speed	400 miles per hour (587 fps)
Width of inlet and outlet	25 inches
Position of inlet . . .	12 feet aft of fuselage nose

Assume the expansion to be effected with three passages.

The computations proceed in the following steps (table IIIa):

1. $$\delta = 0.37 \left(\frac{\nu}{V_o}\right)^{1/5} x^{4/5} = 0.37 \left(\frac{1.3 \times 10^{-4}}{587}\right)^{1/5} 12^{4/5}$$

$$= 0.126 \text{ foot} = 1.52 \text{ inches}$$

2. Approximately, $i = \dfrac{20000}{60 \times 587 \times 0.6} \times \dfrac{144}{25} = 5.45$ inches

3. $\dfrac{\delta}{i} = \dfrac{1.52}{5.45} = 0.28$, which is intermediate between the first two cases of the table

4. $n = \dfrac{20000}{60 \times 587} \times \dfrac{144}{25 \times 16} = 0.205$

5. $h = \dfrac{n}{\sqrt{0.044 + n^2}} = \dfrac{0.205}{\sqrt{0.044 + 0.042}} = 0.70$; $h\dfrac{r}{3} = 3.74$ inches

6. $f = \dfrac{\dfrac{2n}{1 + h}}{\sqrt{0.27 + n^2}} = \dfrac{\dfrac{0.41}{1.7}}{\sqrt{0.27 + 0.042}} = 0.43$; $f(1+h)\dfrac{r}{3} = 3.9$ inches

7. $\dfrac{e}{r} = \dfrac{n}{\sqrt{0.81 - 5n^2}} = \dfrac{0.205}{\sqrt{0.81 - 0.21}} = 0.264$; $e = 4.2$ inches

8. $\dfrac{i}{r} = \dfrac{n}{0.61} = \dfrac{0.205}{0.61} = 0.336$; $i = 5.4$ inches

9. $\dfrac{g}{i} = 0.40$; $g = 2.2$ inches

10. $\dfrac{j}{i} = 0.35$; $j = 1.9$ inches

11. $\dfrac{l}{i} = 0.36$; $l = 1.9$ inches

REMARKS ON DESIGN

The following points may be noted with regard to design:

1. The nose of the duct (including the sides) should be well rounded and curved slightly inward in order to permit smooth flow of the diverging air over it.

2. The nose of the first vane should be slightly aft of the inlet in order to permit the flow to straighten out before meeting it.

3. The vanes must be built to withstand the differences in static pressure across them (directed toward the fuselage). For the vane nearest the fuselage, the difference may be of the order of 20 percent of the free-stream dynamic pressure. The static pressure within the duct, tending to blow it away from the fuselage, is of the order of the full free-stream dynamic pressure.

4. The sides of the duct should be faired into the fuselage skin so that the rotating slipstream may flow over it smoothly.

5. A flap should be provided, for the climb condition, that will permit the outlet to be enlarged several times. A flap on the inlet will permit a slight further increase in the cooling air for climb, but the presence of the vanes will complicate the design.

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2. Patterson, G. N.: Modern Diffuser Design. Aircraft Engineering, vol. 10, no. 115, Sept. 1938, pp. 267-273.

3. Freeman, Hugh B.: Measurements of Flow in the Boundary Layer of a 1/40-Scale Model of the U.S. Airship "Akron." Rep. No. 430, NACA, 1932.

L-321

TABLE I

Duct Drag Analysis

[Drag in percent of the total drag for the condition of rear vanes in]

	$\frac{\Delta p}{q} = 4$		$\frac{\Delta p}{q} = 40$	
	Rear vanes in	Rear vanes out	Rear vanes in	Rear vanes out
Expansion loss	23		9	
Loss across screen	37	115	75	116
Losses behind screen	12		3	
Drag of duct sides and top	28	28	13	13
Total	100	143	100	129
Ideal drag $\frac{q\Delta p}{V_0}$	34	34	65	65
Efficiency, percent	34	24	65	50

TABLE II

Distribution of Flow, Rear Vanes Out

[Values in percent of total flow]

Section	$\frac{\Delta p}{q} = 4$	$\frac{\Delta p}{q} = 40$
Top	56	39
Second	14	33
Third	25	21
Bottom	5	7
Total	100	100

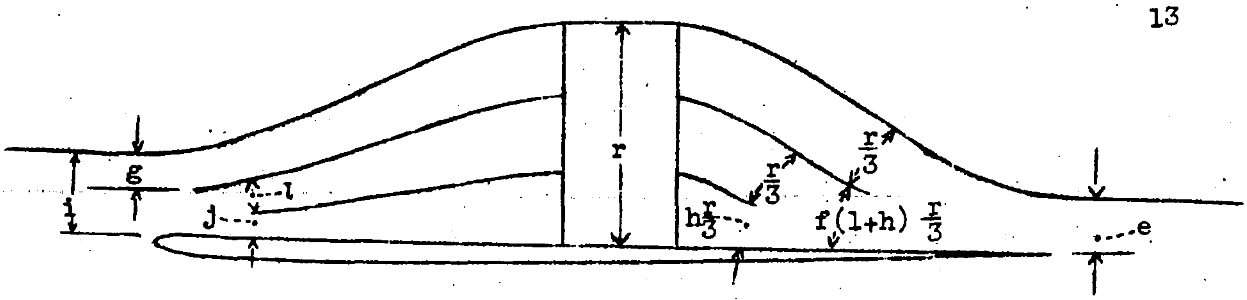


TABLE IIIa.- Three-Passage Duct Dimensions

Given: r, height of radiator

k, $\frac{\Delta p}{q}$ for radiator

n, $\frac{\text{velocity at radiator}}{\text{free-stream velocity}}$

δ, boundary layer thickness

	$\frac{\delta}{i} = 0.25$	$\frac{\delta}{i} = 0.31$	$\frac{\delta}{i} = 0.50$	$\frac{\delta}{i} = 0.94$
h	$\frac{n}{\sqrt{.030 + n^2}}$	$\frac{n}{\sqrt{.057 + n^2}}$	$\frac{n}{\sqrt{.085 + n^2}}$	$\frac{n}{\sqrt{.076 + n^2}}$
f	$\frac{\frac{2n}{1 + h}}{\sqrt{.25 + n^2}}$	$\frac{\frac{2n}{1 + h}}{\sqrt{.28 + n^2}}$	$\frac{\frac{2n}{1 + h}}{\sqrt{.23 + n^2}}$	$\frac{\frac{2n}{1 + h}}{\sqrt{.19 + n^2}}$
$\frac{e}{r}$	$\frac{n}{\sqrt{.82 - kn^2}}$	$\frac{n}{\sqrt{.80 - kn^2}}$	$\frac{n}{\sqrt{.77 - kn^2}}$	$\frac{n}{\sqrt{.66 - kn^2}}$
$\frac{i}{r}$	$\frac{n}{0.63}$	$\frac{n}{0.59}$	$\frac{n}{0.57}$	$\frac{n}{0.50}$
$\frac{g}{i}$	0.40	0.40	0.40	0.40
$\frac{j}{i}$	.35	.34	.33	.32
$\frac{l}{i}$	.36	.37	.38	.39

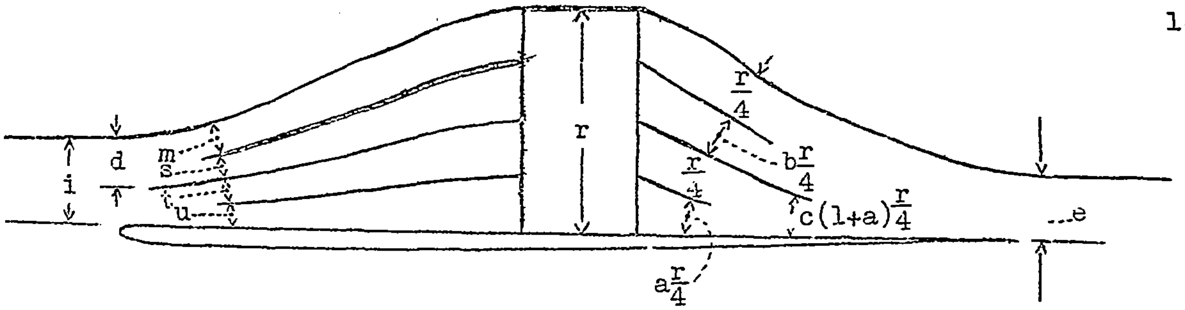


TABLE IIIb.- Four-Passage Duct Dimensions

Given: r, height of radiator

k, $\frac{\Delta p}{q}$ for radiator

n, $\frac{\text{velocity at radiator}}{\text{free-stream velocity}}$

δ, boundary layer thickness

	$\frac{\delta}{i} = 0.25$	$\frac{\delta}{i} = 0.31$	$\frac{\delta}{i} = 0.50$	$\frac{\delta}{i} = 0.94$
a	$\frac{n}{\sqrt{.014 + n^2}}$	$\frac{n}{\sqrt{.038 + n^2}}$	$\frac{n}{\sqrt{.063 + n^2}}$	$\frac{n}{\sqrt{.048 + n^2}}$
b	$\frac{n}{\sqrt{.36 + n^2}}$	$\frac{n}{\sqrt{.19 + n^2}}$	$\frac{n}{\sqrt{.18 + n^2}}$	$\frac{n}{\sqrt{.14 + n^2}}$
c	$\frac{\frac{n}{1+a}}{\sqrt{.046 + \left(\frac{n}{1+b}\right)^2}}$	$\frac{\frac{n}{1+a}}{\sqrt{.051 + \left(\frac{n}{1+b}\right)^2}}$	$\frac{\frac{n}{1+a}}{\sqrt{.054 + \left(\frac{n}{1+b}\right)^2}}$	$\frac{\frac{n}{1+a}}{\sqrt{.040 + \left(\frac{n}{1+b}\right)^2}}$
$\frac{e}{r}$	$\frac{n}{\sqrt{.82 - kn^2}}$	$\frac{n}{\sqrt{.80 - kn^2}}$	$\frac{n}{\sqrt{.77 - kn^2}}$	$\frac{n}{\sqrt{.66 - kn^2}}$
$\frac{i}{r}$	$\frac{n}{0.63}$	$\frac{n}{0.59}$	$\frac{n}{0.57}$	$\frac{n}{0.50}$
$\frac{d}{i}$	0.35	0.55	0.55	0.55
$\frac{m}{i}$	.36	.35	.34	.34
$\frac{s}{i}$	.29	.29	.30	.30
$\frac{t}{i}$	.27	.27	.28	.28
$\frac{u}{i}$	.26	.26	.25	.25

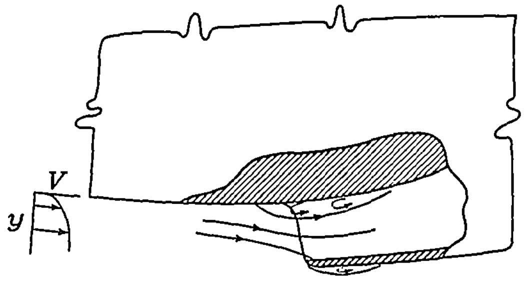
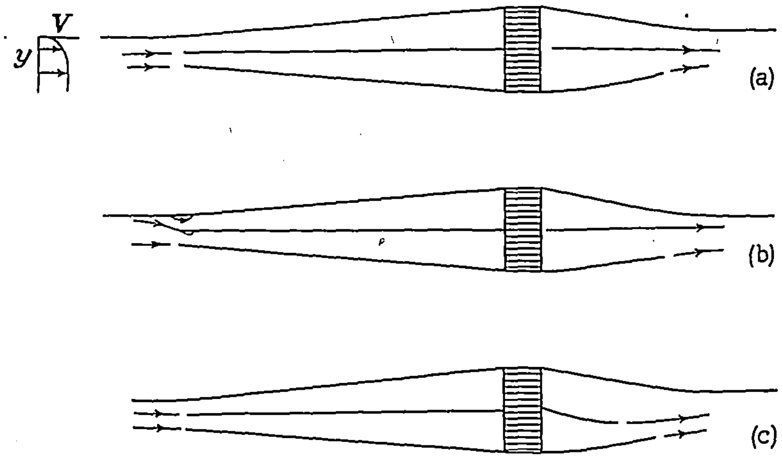


Figure 1.- The breakaway of a boundary layer before an oversize duct inlet.



(a) Flow equally divided, rear vane absent, an impossible condition.
(b) Flow unequally divided, rear vane absent.
(c) Flow equally divided, rear vane placed to constrict the lower passage.

Figure 2.- The flow of a boundary layer in a divided duct.

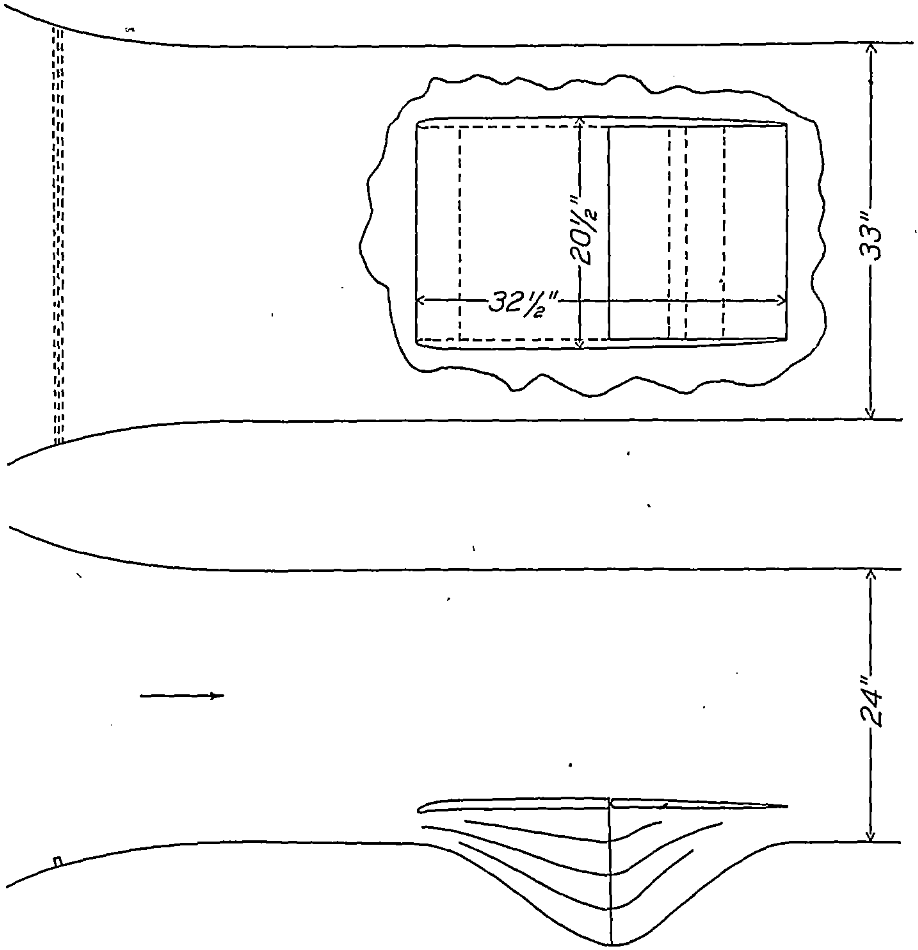


Figure 3.- Plan view and longitudinal section of the duct mounted in the wind tunnel.

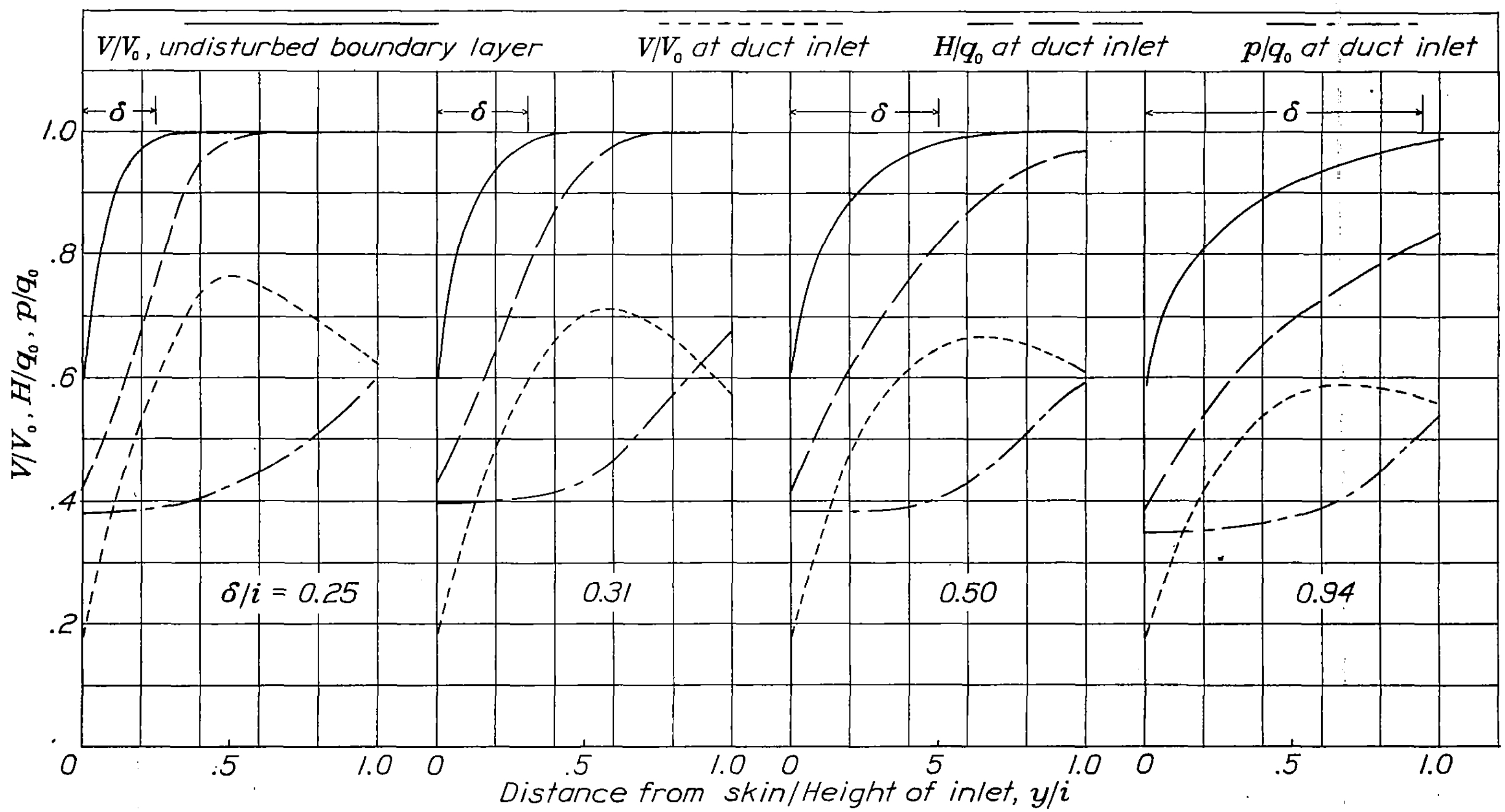


Figure 4.- Characteristics of the optimum expansion of four turbulent boundary layers.